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Discriminating between spherical and non-spherical scatterers with lidar using circular polarization: a theoretical study

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Abstract

For ground based observations, depolarization of lidar backscatter indicates that the scattering particles are non-spherical. This property provides a useful means to discriminate between ice particles (non-spherical) and water droplets (spherical) in clouds. However, for space based lidar measurements, backscatter from spherical water cloud particles is also depolarized due to multiple scattering. For the spaceborne lidar application, the discrimination between water and ice is not straightforward.

An alternative method for water/ice discrimination that is less sensitive to multiple scattering is proposed in this study. The new approach is based on the differences in P_{44} (an element of the scattering phase matrix) at 180° scattering angle between spherical and non-spherical particles. By transmitting a circularly polarized beam from the lidar and resolving the rotational sense of the polarization in the receiver, discrimination between spherical and non-spherical scatterers can be accomplished even when multiple scattering occurs. When the incident beam is left-hand-circularly polarized, the circular component of backscatter by a non-spherical particle is weak and possibly left-handed, whereas backscatter by a spherical particle is significantly right-hand-circularly polarized. Monte Carlo simulations with full Stokes vector parameterizations indicate that multiple scattering does not affect the rotational sense of the backscatter polarization, making robust discrimination between spheres and non-spheres possible with this new circular polarization approach.
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1. Introduction

Retrievals of optical thickness and effective particle size of a cloud from radiometric measurements depend critically on assumptions on the shape of the cloud particles. If cloud particle shape is unknown, uncertainties arise in the interpretation of the spectral and angular radiometric

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measurements. If, for instance, we know that cloud particles are spherical, we can select water cloud refractive indices at all wavelengths and take advantage of spectral correlations. We can also determine the scattering phase functions. Knowledge of cloud particle shape information is also important in making accurate cloud measurements with lidar. Cloud particle shape information is needed to estimate the values of the extinction-to-backscatter ratio and multiple scattering factor used in the retrieval of backscatter and extinction. In addition, there is a wide range of applications of optical particle characterization in other fields which require knowledge of particle shape. Such applications include medical imaging, environmental monitoring, and applications in the pharmaceutical industry.

In cloud remote sensing, particle shape is determined either directly or indirectly. The indirect method assumes that spherical particles are water and non-spherical particles are ice. As the absorption and emission by water and ice are very different in infrared and near-infrared wavelengths, cloud phase (water or ice) can be estimated from the spectral signature of the cloud radiometric measurements [1]. Direct methods use polarization characteristics as well as their angular and spectral correlation patterns to separate spherical particles and various non-spherical particles [2–4]. The Polarization and Directionality of Earth's Reflectances (POLDER) instrument, with its multi-angle view and dual polarization measurements, uses the spherical particle internal reflection (rainbow) polarization characteristics to identify water clouds [5]. The space-based Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) [6] will identify spherical particles by analysis of depolarized lidar backscatter signals [4,7–11]. Like all standard polarization-sensitive lidars, the CALIPSO laser beam is linearly polarized. When clouds are optically thin and single scattering dominates, the backscatter from spherical particles is not depolarized, making the perpendicularly polarized component of backscatter very nearly zero. For randomly oriented non-spherical particles, backscattering is highly depolarized.

Unlike ground-based lidar systems for which the targets are relatively close, the horizontal span of the atmospheric volume imaged within the receiver field of view (i.e., the "footprint") of the space based CALIPSO lidar is relatively large (around 90 m), making the likelihood of detecting multiply scattered photons large for all but the most tenuous targets. The multiple scattered photons introduces ambiguity in water/ice discrimination. For water (spherical) particles, multiple scattering, particularly side scattering, causes depolarization. Thus, the backscattering signals from dense water clouds are depolarized when higher order scattering dominates. As a result, the measured perpendicularly polarized backscatter signal is similar to that originated from ice clouds. For dense, non-absorbing media, multiple scattering effects preclude the use of linear depolarization measurements to identify particle spherocity. This paper presents an alternative means of discrimination with less sensitivity to multiple scattering.

Whereas the previous approach relies on linear depolarization characteristics, this paper exploits the differences in circularly polarized backscattering characteristics between spherical and non-spherical particles. To take advantage of these differences, the transmitted laser beam must be circularly polarized, which can be easily achieved with a quarter-wave plate. The lidar receiver must be designed to resolve the rotational sense of the incident polarization (i.e., either left- or right-handedness of the backscattered light) and record both the total intensity and the direction of rotation of the circularly polarized backscatter.

First, we demonstrate how such a system can be used distinguish between spherical and non-spherical particles. We then analyze the sensitivity of the technique to multiple scattering by simulating the scattering process with a full Stokes vector Monte Carlo code [7] developed specifically for lidar applications. The sensitivity will be compared with previous CALIPSO studies concerning the analysis of linear polarization returns.

2. Circular components: differences between spheres and non-spheres

For randomly oriented particles, the Stokes vector of single scattering properties between the incident beam $\{I_0, Q_0, U_0, V_0\}$ and the backscattered light ray $\{I, Q, U, V\}$ is

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{12} & P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & P_{34} \\ 0 & 0 & -P_{34} & P_{44} \end{pmatrix} \begin{pmatrix} I_0 \\ Q_0 \\ U_0 \\ V_0 \end{pmatrix}, \tag{1}$$

where P_{ij} are the elements of the phase matrix [12,8]. Thus, for direct backscatter,

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} I_0P_{11} + Q_0P_{12} \\ Q_0P_{22} + I_0P_{12} \\ U_0P_{33} + V_0P_{34} \\ V_0P_{44} - U_0P_{34} \end{pmatrix}. \tag{2}$$

The elements of the phase matrix for spherical particles are computed from Mie theory. The particle sizes are assumed to conform to a Gamma distribution with a prescribed mode radius and a 10% dispersion.

The improved geometric optics method (IGOM) [13] is used to calculate the scattering properties of several types of ice crystals including aggregates, hexagonal columns and bullet rosettes. The ray tracing technique is employed to calculate the near field on particle surface, with inclusion of complete phase information for the electric field. Subsequently, a rigorous electromagnetic integral equation is applied to map the near field to far field for calculation of single-scattering properties. The procedures to define the three-dimensional geometry for the ice crystals and the surface roughness have been reported previously [14].

2.1. Linear depolarization method for water/ice discrimination

For a standard linear-polarization-sensitive lidar, such as the CALIPSO lidar, the incident beam is linearly polarized. The incident Stokes vector is $I_0\{1, 1, 0, 0\}$. For direct backscatter (scattering angle 180°), $P_{12} = 0$, and, from Eq. (2), the Stokes vector for light directly backscattered into the receiver is $I\{1, P_{22}/P_{11}, 0, 0\}$. For backscatter from spherical particles, $P_{22} = P_{11}$. Thus $I = Q$, and the singly scattered return is not depolarized. For non-spherical (e.g., ice) particles, $P_{22} \neq P_{11}$, and $I \neq Q$, and the singly scattered return is depolarized. Thus, for singly scattered returns, lidar measurements of

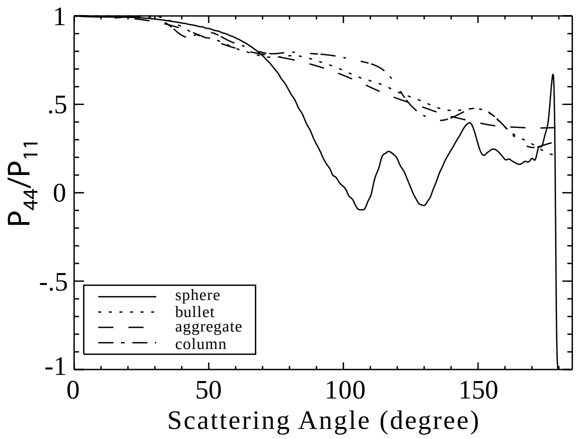

Fig. 1. Differences between the ratio P_{44}/P_{11} for water particles (spheres) and ice particles (aggregates, columns and bullet rosettes).

the perpendicularly polarized backscatter (0.5 times the difference between I and Q) can be used to determine whether the scattering particles are spherical or non-spherical.

2.2. Circular polarization method for water/ice discrimination

By placing a quarter-wave retarder in front of the laser, a linear polarized laser beam can be converted into a circular polarized beam. Assuming now that the beam incident on the scatter is circular polarized (Stokes vector $I_0\{1,0,0,1\}$), from Eq. (2) we see that the Stokes vector for light directly backscattered into the receiver is $I\{1,0,P_{34}/P_{11},P_{44}/P_{11}\}$.

For spherical particles, Fig. 1 shows that P_{44}/P_{11} is -1 at 180° (backscattering); however, the P_{44} elements of non-spherical particles vary with particle size, aspect ratio, particle surface texture (i.e., surface roughness condition), as is shown by the computations carried out by Mishchenko [15,16], Yang and Liou [13,14], as well as experimental results [17]. For cirrus clouds, Mishchenko et al. [18] articulated on the basis of various in situ measurements [19–22] that the phase functions for ice phase clouds are usually featureless without pronounced halo features. One physical mechanism for this featureless phase functions is the effect of ice particle surface roughness. For this reason, we assumed moderate surface roughness [14] for ice crystals in the present single-scattering computation. Under this assumption, P_{44} for non-spherical ice crystals is substantially different from that of spheres, as is evident from one example illustrated in Fig. 1.

The positive and negative sign of the circular polarization component indicate right-hand and left-hand rotation directions, respectively. By measuring the magnitude as well as the rotation direction of the circularly polarized component of the backscattered light, we can discriminate between spherical and non-spherical particles.

Detecting the circular polarization component of the backscattered light is straight-forward. Like most lidars, the backscattered light is collected by a telescope and re-collimated downstream of the field stop. In the collimated beam downstream of the field stop, a quarter wave plate is inserted into the optical path. The quarter wave plate converts the circularly polarized light into light that is polarized at either 45° or 135° from a principal axis, depending on the direction of rotation of the incident circular polarization. The quarter wave plate is followed by a polarizing beamsplitter oriented to separate the linear polarization components (i.e., orientated at 45° to one of the principal axes of the quarter wave plate). Separate detectors measure the two linearly polarized beams emanating from the polarizing beam splitter. The difference between the two signals determines the rotation direction of the incident circularly polarized light and the sum determines the magnitude of the total backscatter signal.

3. Multiple scattering: comparisons of linear and circular approaches

For media dominated by single scattering, such as optically thin media and absorbing media, it is possible to use either the linear or circular depolarization technique to discriminate between spherical and non-spherical particles. For a non-absorbing scattering medium which is optically thick, the polarization state of the backscattered light becomes much more complicated. We employed Monte Carlo simulations with full Stokes vector parameterization to investigate the polarization state of multiply scattered light.

The statistical concept of our Monte Carlo scheme [7] is similar to the ray tracing technique. Various noise reduction methods [23,24] are applied to speed up the convergence of the scheme. Instead of tracing each photon to determine its path through the medium, analytic estimates are made at every scattering event to determine the probability that the photon will enter the lidar receiver without further interaction (absorption or scattering) with the medium [7]. Different from scalar Monte Carlo radiative transfer methods, the Stokes vector Monte Carlo scheme traces the full polarization state, providing greater accuracy at the expense of computation time.

The multiple scattering contribution to the total backscatter increases with increasing receiver field of view angle (FOV) and distance between the receiver and the target. For the Monte Carlo simulations, the CALIPSO orbit altitude is assumed to be 705 km and the lidar FOV is set to 0.13 mrad. The medium is assumed to be 1 km thick and results were computed at various values of extinction coefficient.

Figs. 2–4 are the multiple scattering effects on backscatter polarization derived from Monte Carlo simulations. Fig. 2 shows that column integrated backscatter from spherical particles depolarizes when the scattering media becomes more dense. The depolarization ratios for spherical particles can be as large as 50%. The depolarization ratios are not as large as those for certain types of randomly oriented non-spherical particles with similar backscattering intensities. Considering that there are oriented plates in ice clouds, for which the linear depolarization ratio is small, it takes only a small amount of oriented plates to reduce the depolarization ratios of ice clouds significantly to the levels where we can no longer distinguish between dense water clouds and ice clouds. Thus, the combination of multiple scattering and the possible presence of oriented plates reduces the confidence level of cloud phase (water/ice) discrimination using the linear depolarization technique.

The circular polarization method for water/ice discrimination is less sensitive to multiple scattering. Fig. 3 shows that the circular depolarization components of the backscatter have different signs for spherical and non-spherical particles, regardless of the magnitude of the extinction coefficient. Fig. 4 shows that for a semi-infinite layer of non-absorbing scattering particles within an absorbing media, the circular polarization components between spherical and non-spherical particles always

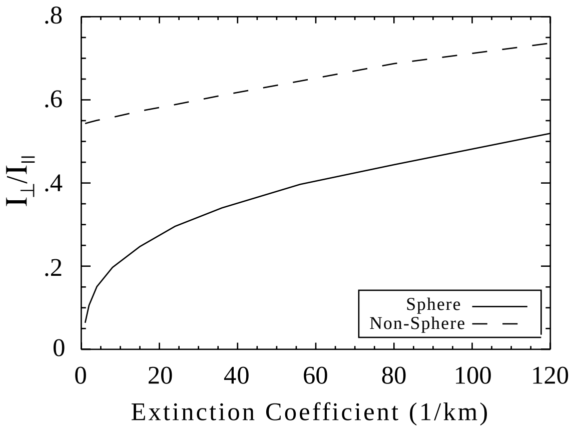

Fig. 2. Impact of multiple scattering on linear depolarization and water/ice discrimination: depolarization of water cloud backscatter (column integrated) increase with increasing extinction coefficient as a result of increased multiple scattering.

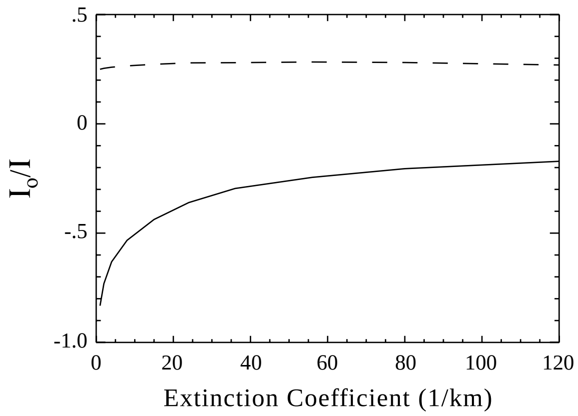

Fig. 3. Impact of multiple scattering on circular polarization and discrimination between spherical and non-spherical scatterers as a function of extinction coefficient: circular component V for spherical particles is always negative, while V for non-spherical particles are mostly positive.

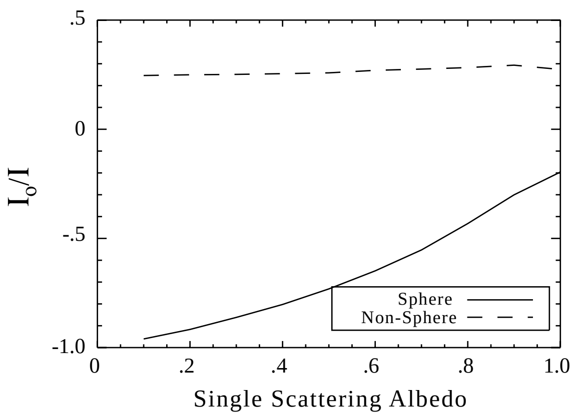

Fig. 4. Impact of multiple scattering on circular polarization and discrimination between spherical non-spherical scatterers for semi-infinite layer with varying absorption.

have different sign, regardless of the magnitude of the absorption. The results shown in Figs. 3 and 4 show that there is little ambiguity in the discrimination between spherical and non-spherical particles using the circulation polarization technique, even for optically thick media where multiple scattering is significant.

Comparing with measuring linear components, deciding the circulation polarization rotation direction requires less effort than accurately estimating the magnitude of linear polarization components.

4. Summary

One of the most common techniques for distinguishing between spherical and non-spherical particles involves measuring the linear polarization components of backscatter, using a linearly polarized laser beam as the source. For spherical particles, the backscattered light is not depolarized ($I-Q=0$), whereas for non-spherical particles, the backscattered light is depolarized ($I - Q > 0$). This technique works well when the backscatter is dominated by single scattering, but leads to ambiguity when multiple scattering dominates.

This study outlines an alternative technique. based on measuring circular polarization components of backscatter, using a circularly polarized beam as the source. It is easy to convert a linearly polarized laser beam into circularly polarized light with a quarter-wave retarder. The circularly polarized component of light backscattered by spherical particles rotates in the opposite direction to that of the circularized laser beam. For non-spherical particles, the direction of rotation remains the same as that of the laser beam. The advantage of using measurements of the rotating direction of circular polarization components over linear depolarization measurements is that discrimination between spherical and non-spherical scatterers is possible for both single and multiple scattered photons.

Simulations with a full Stokes vector Monte Carlo radiative transfer model were performed to quantitatively assess the impact of multiple scattering on the effectiveness of the two techniques for discrimination between spherical and non-spherical scatterers. The contribution of multiple scattering to the total return increases with extinction coefficient, particle single scattering albedo, receiver field of view, and range to the target. For spaceborne lidars, the range to the target is very large, making the multiply scattered component of the backscatter significant for clouds and the discrimination of cloud phase ambiguous using the standard linear polarization technique.

The new technique based on the measurement of circularly polarized backscatter is a more effective method for discrimination between spherical and non-spherical particles even when multiple scattering occurs.

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